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The study was done to determine whether thermal comfort (TC), thermal sensation (TS), and subjective factors gauging environmental stress were negatively affected with different cooling methods in men exercising in chemical protective clothing. Previous studies have reported that intermittent regional cooling improved the efficacy of cooling as compared with constant cooling (CC), but no studies have addressed whetehr there is any improvement in thermal comfort. Eight male volunteers exercised at moderate work intensity (425 W) in three microclimate cooling tests. The circulating fluid in the cooling garment was provided during exercise to the head (6% body surface area [BSA]), torso (22% BSA), and thighs (44% BSA) and manipulated under three methods: (a) CC, (b) pulsed cooling (PC), and (c) PC activated by mean skin temperature (Tsk) control (PCskin). TC and TS ratings were recorded every 20 min during the 80-min test. TC and TS ratings were not different for PCskin and CC; thus the participants perceived PCskin and CC ($p < .001$). In PCskin, Tsk was significantly higher than in PC and CC ($p < .001$), and PCskin was rated as being not as warm as PC according to TS. This indicates that the PCskin method was perceived as being as cool as CC and cooler than PC. These findings indicate that the PCskin cooling method is an acceptable alternative to CC and PC based on human perceptions.

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Thermal Comfort and Sensation in Men Wearing a Cooling System Controlled by Skin Temperature

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Objective: The study was done to determine whether thermal comfort (TC), thermal sensation (TS), and subjective factors gauging environmental stress were negatively affected with different cooling methods in men exercising in chemical protective clothing. **Background:** Previous studies have reported that intermittent regional cooling improved the efficacy of cooling as compared with constant cooling (CC), but no studies have addressed whether there is any improvement in thermal comfort. **Methods:** Eight male volunteers exercised at moderate work intensity (425 W) in three microclimate cooling tests. The circulating fluid in the cooling garment was provided during exercise to the head (6% body surface area [BSA]), torso (22% BSA), and thighs (44% BSA) and manipulated under three methods: (a) CC, (b) pulsed cooling (PC), and (c) PC activated by mean skin temperature ($\overline{T}_{sk}$) control (PC_{skin}). TC and TS ratings were recorded every 20 min during the 80-min test. **Results:** TC and TS ratings were not different for PC_{skin} and CC; thus the participants perceived PC_{skin} as being similar to CC. TS was significantly warmer with PC than with PC_{skin} and CC ($p < .001$). In PC_{skin}, $\overline{T}_{sk}$ was significantly higher than in PC and CC ($p < .001$), and PC_{skin} was rated as being not as warm as PC according to TS. **Conclusion:** This indicates that the PC_{skin} method was perceived as being as cool as CC and cooler than PC. **Application:** These findings indicate that the PC_{skin} cooling method is an acceptable alternative to CC and PC based on human perceptions.

INTRODUCTION

Previously it was reported that intermittent regional cooling, as compared with a constant cooling paradigm, improved the efficacy of cooling exercising men wearing chemical protective clothing (Cheuvront, Kolka, Cadarette, Montain, & Sawka, 2003). Heat removal was significantly improved because mean skin temperature ($\overline{T}_{sk}$) and, consequently, skin blood flow remained elevated for more time in the body regions supplied with regional cooling, having the effect of decreasing the insulation of the body surface and increasing radiative, convective, and conductive heat loss. Importantly, regional cooling was achieved with reduced circulation of the cooled fluid, presumably making dissipation of body heat more efficacious. The study did not address whether or not regional cooling resulted in a similar improvement in user comfort.

The rationale for the research was that any cooling paradigm that improved or maintained the user's cardiovascular and thermoregulatory integrity would improve the user's comfort when he or she exercised while wearing chemical protective clothing. Consequently, this study was initiated to further improve the cooling paradigm to optimize cooling and power conservation. The users' subjective ratings of how the new cooling paradigm made them feel relative to constantly supplied cooling were measured. In the current study, the participants' perception of thermal sensation and thermal comfort was determined to further support the effectiveness of pulsed cooling based on skin temperature feedback from subjective ratings by the user.

The physiological approach used in our laboratory to improve cooling efficacy focused on retaining a warm skin so that the cutaneous vasculature remains vasodilated at a level that supports rapid

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convective and radiative heat loss once cool liquid circulates. This provided a microenvironment appropriate for heat transfer away from the body.

The research aim was to further improve efficiency in cooling by using pulsatile cooling controlled by temperature sensors placed on the skin (PC_{skin}), so that real-time $\overline{T}_{sk}$ could be used to activate the fluid-circulating pump when $\overline{T}_{sk}$ increased 1.5°C above thermoneutral skin temperature. When the warm skin was cooled to a temperature of 33.5°C (slightly warmer than thermoneutral skin temperature), the pump was automatically deactivated. Kolka et al. (2004) documented the heat transfer properties of this most recent physiologic, integrative approach used in our laboratory to optimize microclimate cooling. In addition, Stephenson, Vernieuw, Leammukda, and Kolka (2007) described these findings in greater detail. In short, integrating the individual's $\overline{T}_{sk}$ response to activate cooling was as effective as constant cooling and time-activated pulsed cooling to improve heat dissipation in men exercising in protective clothing. This improved efficacy occurred with a 46% reduction in electrical power used.

Thermal comfort (TC) was chosen as a measure because it was suspected that using the word "comfort" might help the participants integrate thermal sensation (TS) with the burden of exercise and wearing the cooling garment. Fanger (1970) defined TC as a "state in which he [the participant] expresses satisfaction with the thermal environment; i.e. he would prefer neither a warmer nor a colder environment" (p. 152). With this said, one would assume that a person's performance would be at his or her best when he or she is thermally comfortable (Fanger, 1970).

TS was used as another measurement for subjective perception to the cooling methods. TS provided specific descriptors for thermal perception from *very cold* to *very hot,* and this scale includes a reference to *neutral* TS (Berglund, 1998). It is important to point out that thermal balance, clothing, ambient temperature, ambient dew-point temperature, wind speed, radiant temperature, clothing, and metabolism all affect TS (Berglund, 1998). In the current study, the participants were not in thermal balance across the entire exercise bout, so one has to view TS and TC perception as a composite indicator for all the factors at the time of the measurement. The many factors that influence TC and TS were $\overline{T}_{sk}$, local skin temperature sites with and without cooling, core temperature, the liquid flow rate in the cooling garment, the temperature of the liquid in the cooling garment at the skin, heart rate, skin wettedness, clothing, and metabolism.

The participants' perception of the entire experiment was measured using the Environmental Symptoms Questionnaire (ESQ), a measurement of subjective responses to extreme environments (Sampson, Kobrick, & Johnson, 1994). Embedded within the ESQ are five indices and nine factors. In the current study the most relevant indices were subjective heat illness, muscle discomfort, cardiopulmonary discomfort, tiredness, and well-being. The most relevant factors determined from the ESQ were distress, alertness, exertion, muscle discomfort, and fatigue.

The purpose of this research was to determine whether TC, TS, and subjective factors and indices from the ESQ were negatively affected in men exercising in chemical protective clothing when the cooling characteristics of fluid circulating through the cooling garment were changed. The research hypothesis was that the participants would perceive all cooling methods as equally cool.

METHODOLOGY

The study was approved by institutional review boards based on scientific and human research review, and the investigators adhered to Army Regulation 70-25 and U.S. Army Research Institute of Environmental Medicine 70-25 on Use of Volunteers in Research. All participants were briefed regarding the risks and requirements to participate in the study. Participants who agreed to participate signed the consent form and then were medically cleared.

Participants

Eight young, healthy, and fit men volunteered for this study: age 20.6 ± 1.7 years, height 175 ± 0.05 cm, weight 73.14 ± 7.45 kg, body surface area (BSA) 1.90 ± 0.11 m², and body mass index (BMI) 24.7 ± 1.3 (mean ± *SD*). Women were not studied because none volunteered to participate.

Experimental Procedures

Prior to testing, participants were thoroughly familiarized with all experimental techniques and fitted with the proper-sized liquid cooling garment, chemical protective clothing, and protective

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mask. Participants were not heat acclimated prior to testing. All testing took place in October in Natick, Massachusetts. Participants were given an explanation of TC and TS and the proper way to express their comfort and sensation on the scale provided during testing.

Two participants were tested each week, one in the morning (10:00) and one in the early afternoon (12:30), at the same time on 3 consecutive testing days to complete the three methods for the different tests. Participants ingested a temperature pill sensor (HQ, Inc., Palmetto, FL) to allow measurement of core temperature, which was telemetered to a data logger and temperature monitor (FitSense, Inc., Southborough, MA).

After arriving at the laboratory, the participants drank 120 ml of water. During the experiment, no other fluid intake took place. Each participant's seminude body mass was determined using an electronic precision balance scale accurate to ±50 g (Toledo ID1 Multirange, United Scale & Engineer Corp., New Berlin, WI). The participants then dressed in the inner clothing worn for the test. The participants were instrumented with skin temperature/heat flow thermistors, electrocardiogram electrodes, a heart rate monitor (Polar Watch, Polar CIC Inc., Port Washington, NY), and the core temperature monitor. Participants were then fitted with the cooling garment (middle layer of clothing), chemical protective clothing, and M-40 chemical-biological field mask with hood (outer clothing layer).

Body mass was recorded with all equipment on, before the exercise began. Core temperature (T_c) and $\overline{T}_{sk}$ were measured every minute. Heart rate (HR) was monitored continuously and recorded every 5 min using the Polar heart rate telemetry system and checked with an electrocardiography recording system (Cardiovit AT-6, Schiller AG, Switzerland) for safety purposes. TC and TS estimations were recorded every 20 min (Time 0, 20, 40, 60, and 80 min). Metabolic rate was measured by open-circuit spirometry (True Max 2400 Parvomedics, Inc., Sandy, UT) during the last 5 min of exercise for a 3- to 4-min duration after removal of the protective mask and hood. Once exercise was complete, participants were weighed again to determine body mass with all equipment and the seminude body mass.

Clothing. Participants dressed the same for each trial. The personal layer of clothing consisted of spandex shorts, cotton socks, and athletic shoes. The cooling layer was a three-piece liquid cooling garment that covered the head (hood), torso (vest), and legs (pants). The layer worn was composed of a chemical protective suit that included a charcoal-impregnated overgarment (top and bottom), cotton glove liners, butyl gloves, and a M-40 chemical-biological field mask with hood. This clothing configuration provided approximate insulative value and vapor permeability characteristics of 2.1 and 0.32, respectively, based on still air copper manikin studies (Kolka, Stephenson, & Gonzalez, 1994).

The liquid cooling garment design consisted of cotton or Nomex® aramid fabric, depending on skin region, woven or laminated around small-diameter Tygon® tubing (internal diameter 2.5 mm) divided into multiple parallel circuits. The tubing length for the suit was estimated to be ~108 m. Total BSA covered was estimated in a previous study to be 72% (head = 6%, torso = 22%, and legs = 44%) using a Cyberware® three-dimensional head and whole body scanner (Cyberware, Inc., Monterey, CA; Cheuvront et al., 2003).

The cooling garment was connected to a temperature-controlled recirculating water bath through inlet-outlet umbilical tubes exiting the garment at the waist (torso and legs) or collar (head). The total flow rate for constant cooling was 1.2 L/min, and inlet water temperature was 21.5°C. Pulsed cooling and PC_{skin} flow rates were also 1.2 L/min when the perfusate was circulating. The cooling system was run off an independent power supply, which allowed the measurement of voltage and current usage during each of the three cooling tests. Flow rates and inlet-outlet temperature were also measured.

Design. All three tests were done in a warm, dry environment (dry bulb temperature = 30°C; dew-point temperature = 11°C, equivalent to 30% relative humidity). Participants walked on a treadmill for 80 min during each of the three experiments (1.36 m/s, 2% grade, ~225 W/m^2; 425 W, wind speed 0.939 m/s). The circulating fluid for each region was controlled and manipulated under one of three methods for each test: (a) constant cooling (CC) provided continuous liquid cooling throughout exercise to all regions; (b) pulsed cooling was provided for 2 min, and then the circulating pump was deactivated for 2 min in alternating cycles (PC); (c) pulsed cooling was achieved by control of $\overline{T}_{sk}$ in which cooling was activated at 34.5°C and deactivated when $\overline{T}_{sk}$ decreased to 33.5°C (PC_{skin}).

Calculations

We calculated $\overline{T}_{sk}$ from the formula (Stephenson et al., 2007)

$$\overline{T}_{sk} = 0.07T_{head} + 0.10T_{upper\ back} + 0.10T_{lower\ back} + 0.10T_{chest} + 0.10T_{abdomen} + 0.14T_{forearm} + 0.19T_{thigh} + 0.20T_{calf}.$$

The subscripted type identifies the location where each temperature was measured.

TC and TS measurements were taken at 20-min intervals (Time 0, 20, 40, 60, and 80 min). The data sheet used for each was an open-ended magnitude estimation scale that was a 122-mm line with two labeled categories: *warm* and *cool* for TS and *discomfort* and *comfort* for TC on a scale adapted from Gagge, Stolwijk, and Saltin (1969; see Tables 1 and 2). The open-ended scale was devised to eliminate some of the constraints often imposed by a category scale (Marks, Borg, & Ljunggren, 1983). TS results were then identified on a 5-point scale of *cool* through *neutral* to *warm*. TC results were rated similarly, but on a 4-point scale of *comfortable* to *very uncomfortable* (Gagge et al., 1969).

Data were analyzed using commercial software (SigmaStat, SPSS Science, Chicago, IL). ANOVA (treatment by time) with repeated measures was performed on $\overline{T}_{sk}$, TC and TS, HR, power, T_c, cooling, and time of day. Tukey's HSD post hoc test was applied when significant or interaction events were found. When the test of normality failed with two-way repeated measures, which is often attributable to small sample size and the conservative nature of the test, the Holm-Sidak test was used. Statistical significance was set at $p < .05$.

RESULTS

Perception Effects for Cooling Method

In the current study, the participants did not perceive any difference in TC among CC, PC, and PC_{skin} (Table 3). However, they discerned differences in TS among the cooling paradigms (Table 4, $p \leq .001$). TS was rated significantly warmer in PC than in either CC or PC_{skin} ($p \leq .001$). There was no significant difference for TS between CC and PC_{skin}. TS averaged *slightly warm* (approximately +5) for PC but was closer to *neutral* (+4) for CC and PC_{skin}.

Figure 1 shows mean differences in TC and TS for the three cooling paradigms as a function of time of the experiment. The mean HR and $\overline{T}_{sk}$ are also presented to show that there were no significant differences in HR, but the $\overline{T}_{sk}$ averaged (means with *SD*s in parentheses) 32.33°C (0.89°C) during CC, 33.19°C (0.52°C) during PC, and 33.86°C (0.42°C) during PC_{skin}, all significantly different from each other ($p \leq .001$). This is particularly important because TS was rated higher in PC than in PC_{skin}.

The ESQ responses were similar among the three cooling paradigms, further indicating that heat strain was perceived similarly among participants in all conditions (Table 5). This is verified by similar changes in core temperature and heart rate (Table 6). Table 5 shows the data for the indices and factors of interest for the ESQ in the current study. Note that the cooling methods did not discriminate among either negative or positive factors on the ESQ (Sampson et al., 1994).

Perception Effects for Experimental Time

TC was significantly lower during the last

TABLE 1: Thermal Comfort

Gagge et al., 1969	Numerical Code	Open-Ended Rating	Percentage
Very uncomfortable	4	Discomfort	100% 75%
Uncomfortable	3		60% 50%
Slightly uncomfortable	2		35% 25%
Comfortable	1	Comfort	10% 0%

TABLE 2: Thermal Sensation

Gagge et al., 1969	Numerical Code	Open-Ended Rating	Percentage
		Warm	100%
Warm	6		90%
			80%
			77.50%
Slightly warm	5		70%
			60%
			57.50%
Neutral	4		50%
			40%
			37.50%
Slightly cool	3		30%
			20%
			17.50%
Cool	2		10%
		Cool	0%

minute of exercise (80 min) than at any other time of the experiment ($p = .007$) and averaged approximately 2 (35.35%) or *slightly uncomfortable* (Table 3). At 75 min the hood and mask were removed for measurement of volume of oxygen consumed. Although T_c was at its highest toward the end of exercise, as compared with all other times (Table 6), T_{head} decreased when the hood was removed (T_{head} $p \leq .001$ between trials and Time 0, 20, 40, 60 min vs. 80).

TS was greater at the beginning of the experiment, before walking started and before the cooling was activated (Time 0), as compared with any exercise time when cooling was operational (Times 20, 40, 60, and 80 min), and approximated a rating of +5, or *slightly warm* (70.25% ± 1.07%). TS was lowest at 80 min and was rated approximately +3, or *slightly cool* (36.13% ± 4.92%), after the hood and mask were removed. This rating was significantly different from that at any other experimental time ($p < .05$). TS ratings at 20, 40, and 60 min were not significantly different from one another. For these three exercise times the ratings approximated +4, or *neutral* (Table 4).

Figure 2 shows TS, TC, $\overline{T}_{sk}$, and the flow through the pump (which demonstrates the cooling pump activation and inactivation) for 2 participants, P5 and P8. These participants had similar anthropometric characteristics (P5: BMI = 24.7, BSA = 1.79 m^2, height = 1.68 m, weight = 69.8 ± 0.2 kg; P8: BMI = 24.9; BSA = 1.79 m^2; height = 1.68 m, weight 70.3 ± 0.6 kg), yet their ratings of TS and TC differ considerably, as can be seen on inspection of Figure 2.

P5 perceived himself to be at a *neutral* TS while he was standing in the chamber waiting for the exercise to begin during CC and PC at Time 0. He was *slightly warm* prior to the start of exercise during PC_{skin}. During exercise itself, he was *slightly cool* (Times 20 and 40) to *cool* (Times 60 and 80) during CC, *neutral* (Time 20) to *slightly cool* (Times 40, 60, and 80) during PC, and *slightly cool* (Times 20, 40, and 60) to *cool* (Time 80) during PC_{skin}.

P8, however, perceived the conditions to be warmer. During CC he started off *slightly warm* (Time 0), and once cooling was activated he rated TS as *neutral* (Times 20, 40, 60, and 80). During PC he was *slightly warm* (Times 0, 40, and 60) until the mask came off at the end of exercise, when he felt *neutral*. During PC_{skin} he was *slightly warm* (Time 0) to *neutral* (Time 20) and then *slightly cool* for the last 40 min of exercise. This is also evident when looking at PC_{skin} cooling cycles. P8 cooled more quickly once cooling was activated. P8 thus had nine cooling cycles as compared with P5, who had five cooling cycles.

There was no significant difference in the TC, TS, HR, or $\overline{T}_{sk}$ results between the participants who were tested in the morning and those who were tested in the late morning. There was, however, a significant difference in T_c ($p = .035$) between the

Continued on page 1040

TABLE 3: Mean (*SD*) Thermal Comfort

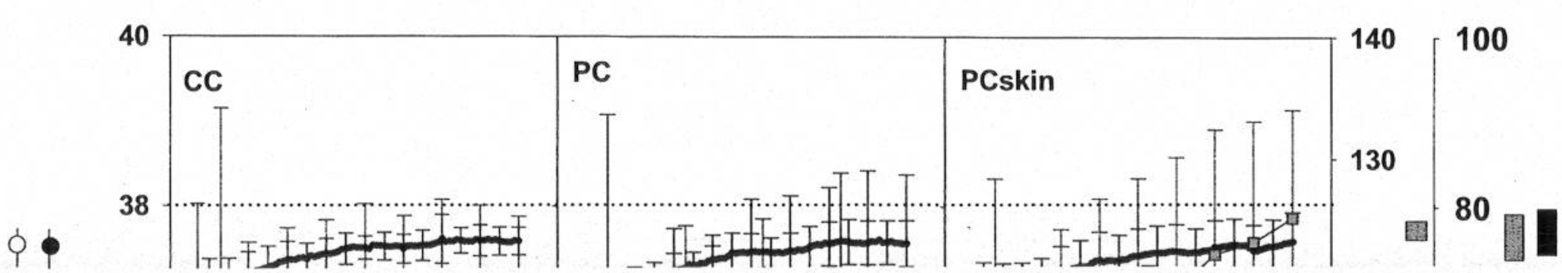
Time (min)	CC (%)	CC Numerical Code	PC (%)	PC Numerical Code	PC_{skin} (%)	PC_{skin} Numerical Code
0: Standing, no cooling	60.6 (19.7)	3 Uncomfortable	49.6 (16.7)	2 Slightly uncomfortable	50.9 (19.1)	3 Uncomfortable
20: Walking	45.7 (20.2)	2 Slightly uncomfortable	53.4 (15.1)	3 Uncomfortable	47.7 (15.0)	2 Slightly uncomfortable
40: Walking	47.6 (9.8)	2 Slightly uncomfortable	53.4 (13.6)	3 Uncomfortable	50.9 (16.5)	3 Uncomfortable
60: Walking	48.0 (13.0)	2 Slightly uncomfortable	55.3 (11.0)	3 Uncomfortable	48.6 (19.9)	2 Slightly uncomfortable
80: Mask off	35.2 (17.1)	2 Slightly uncomfortable	39.4 (19.0)	2 Slightly uncomfortable	31.4 (24.1)	2 Slightly uncomfortable

Note. Main effect by cooling method $p = .265$, *ns*; main effect by time 80 min < 0, 20, 40, 60 min, $p < .050$. CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature.

TABLE 4: Mean (*SD*) Thermal Sensation

Time (min)	CC (%)	CC Numerical Code/TS	PC (%)	PC Numerical Code/TS	PC_{skin} (%)	PC_{skin} Numerical Code/TS
0: Standing, no cooling	71.1 (20.4)	5 Slightly warm	70.6 (20.2)	5 Slightly warm	69.1 (14.3)	5 Slightly warm
20: Walking	43.5 (14.9)	4 Neutral	60.9 (16.9)	5 Slightly warm	45.7 (22.8)	4 Neutral
40: Walking	43.0 (16.8)	4 Neutral	62.6 (16.0)	5 Slightly warm	51.6 (21.5)	4 Neutral
60: Walking	39.3 (18.8)	3 Slightly cool	64.9 (19.2)	5 Slightly warm	45.0 (21.1)	4 Neutral
80: Mask off	32.4 (18.3)	3 Slightly cool	41.7 (21.7)	4 Neutral	34.3 (30.6)	3 Slightly cool

Note. Main effect by cooling method, TS $p < .001$, PC > CC, PC_{skin}; main effect for time, $p < .001$ time 0 > 40, 60, 80 min. CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature, TS = thermal sensation.



60: Walking	39.3 (18.8)	3 Slightly cool	64.9 (19.2)	5 Slightly warm	45.0 (21.1)	4 Neutral
80: Mask off	32.4 (18.3)	3 Slightly cool	41.7 (21.7)	4 Neutral	34.3 (30.6)	3 Slightly cool

Note. Main effect by cooling method, TS $p < .001$, PC > CC, PC_{skin}; main effect for time, $p < .001$ time 0 > 40, 60, 80 min. CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature, TS = thermal sensation.

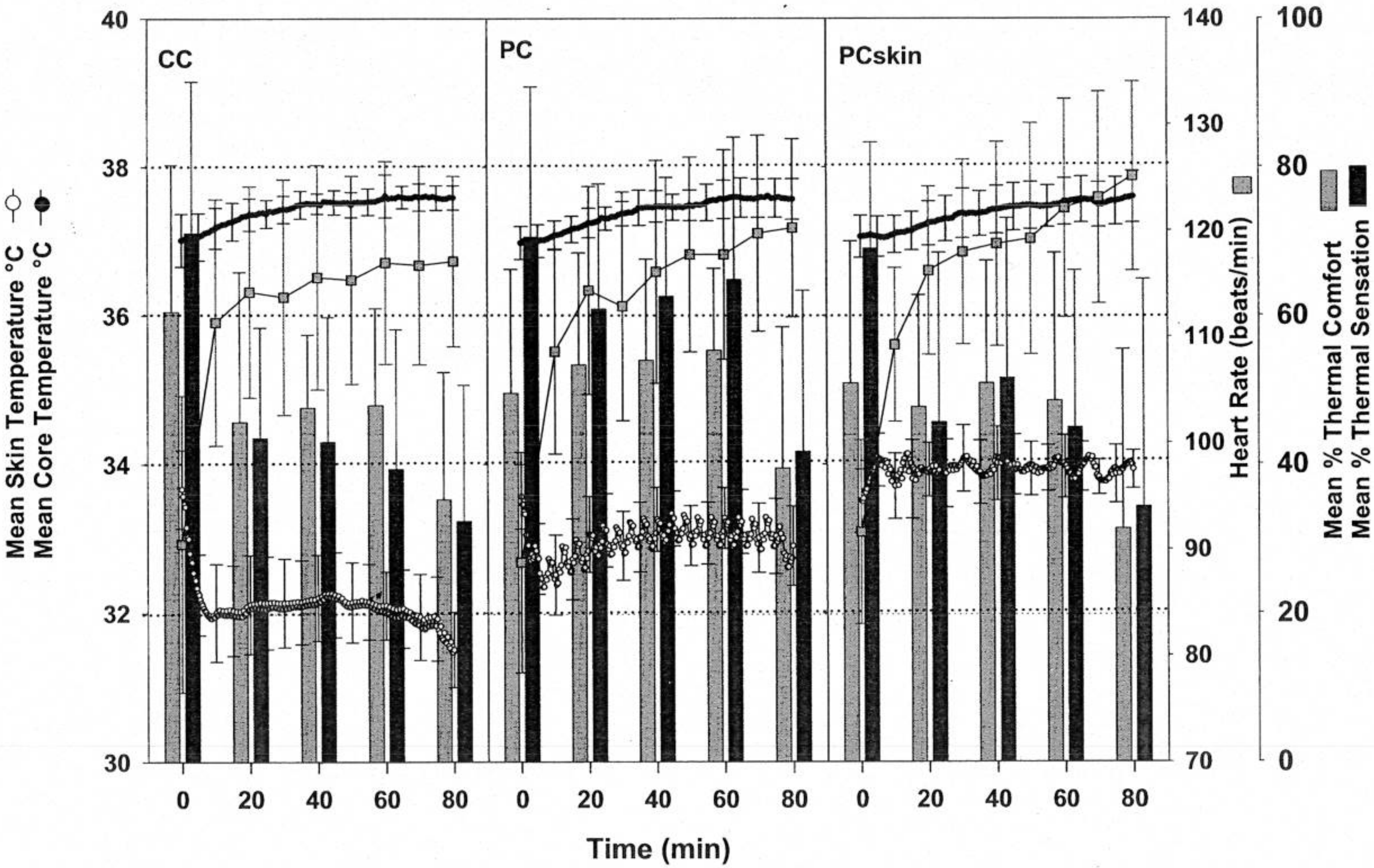


Figure 1. Mean skin temperature ($\overline{T}_{sk}$), core temperature (T_c), heart rate (HR), thermal comfort, and thermal sensation for the three cooling methods (CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature; see text for details). The top line for each panel shows T_c, the middle line shows HR, and the bottom line shows $\overline{T}_{sk}$ ($p < .05$ for TS: PC > CC > PC_{skin} ; $p < .05$ for : CC < PC < PC_{skin}.)

TABLE 5: Mean (*SD*) ESQ Data for Relevant Indices and Factors

Index/Factor	CC	PC	PC_{skin}	*p*
Subjective heat illness index	7.3 (5.5)	6.3 (4.7)	7.0 (5.3)	.5
Cold discomfort index	0	0	0	*ns*
Muscle discomfort index	1.0 (1.8)	0.4 (0.5)	0.8 (0.9)	.4
Cardiopulmonary discomfort index	0.1 (0.4)	0.3 (0.5)	0.4 (0.5)	.3
Tiredness index	1.3 (1.2)	0.9 (1.3)	1.5 (1.4)	.6
Well-being index	4.5 (3.3)	4.0 (2.9)	4.0 (3.7)	.8
Factor 5: Distress	0.2 (0.1)	0.2 (0.2)	0.2 (0.2)	.8
Factor 6: Alertness	3.5 (0.8)	3.3 (0.8)	3.2 (0.6)	.4
Factor 7: Exertion	0.1 (0.1)	0.1 (0.2)	0.1 (0.1)	.6
Factor 8: Muscle discomfort	0.3 (0.3)	0.3 (0.1)	0.3 (0.2)	.6
Factor 9: Fatigue	0.4 (0.3)	0.3 (0.2)	0.4 (0.4)	.7

Note. All different *ps* < .05. ESQ = Environmental Symptoms Questionnaire, CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature.

morning and early afternoon trials, as expected, because of circadian periodicity (Stephenson, Wenger, O'Donovan, & Nadel, 1984).

DISCUSSION

The PC paradigm was designed to use skin temperature feedback to minimize the vasoconstrictor response to pulsatile cooling in the skin so that heat dissipation could be optimized. The most important finding in the current study is that the participants rated TS for PC based on skin temperature (PC_{skin}) as being not as warm as PC and not different from constant cooling, even though $\overline{T}_{sk}$ was higher in PC_{skin} than in constant cooling or PC. In addition, the participants did not find any of the cooling methods to be different as determined by TC ratings, which was to be expected because in every trial the participants received cooling. There were no differences among the cooling paradigms in the ESQ indices and factors, which shows that cooling was adequate for all three to prevent the participants from having symptoms of heat stress during exercise in a warm environment while clothed in chemical protective clothing.

Based on these three observations of the indices of perception, TC, TS, and ESQ, it was concluded from this study that PC based on skin temperature feedback was an acceptable alternative method to CC and PC for cooling, as perceived by the participants.

Under similar conditions in a previous study, there was considerable heat strain when no cooling was provided (Cheuvront et al., 2003). In that study, the participants T_c increased by 1.7 ± 0.3C°, $\overline{T}_{sk}$ averaged 36.5°C to 37.5°C, and heart rate was 81 ± 12 beats per min greater than resting heart rate. These physiological responses in men were similar to those in women when supplemental cooling was not provided during exercise in similar

TABLE 6: Mean (*SD*) Skin Temperature ($\overline{T}_{sk}$), Change in Core Temperature (ΔT_c), Change in Heart Rate (ΔHR), Cooling, and Power

	CC	PC	PC_{skin}
$\overline{T}_{sk}$ (70–75 min)	32.0 (0.6)*	33.1 (0.5)*	33.9 (0.2)*
ΔT_c (0–75 min)	0.5 (0.4)	0.6 (.3)	0.5 (0.3)
ΔHR	26 (10)	30 (9)	31 (10)
Cooling (W)	253 (26)*	196 (17)*	146 (30)*
Electrical power (W)	224 (15)*	169 (16)*	122 (18)*

Note. All different *ps* < .05. Asterisks indicate significant difference. CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature.

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PC$_{skin}$	p
7.0 (5.3)	.5
0	ns
0.8 (0.9)	.4
0.4 (0.5)	.3
1.5 (1.4)	.6
4.0 (3.7)	.8
0.2 (0.2)	.8
3.2 (0.6)	.4
0.1 (0.1)	.6
0.3 (0.2)	.6
0.4 (0.4)	.7

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conditions (Kolka et al., 1994). Clearly, the cooling paradigms used cooled effectively.

The novel paradigm used in this study, of PC based on skin temperature feedback, is essentially an individual prescription for cooling based on real-time $\overline{T}_{sk}$ data. This concept is demonstrated in Figure 2, as the cooling cycles for PC$_{skin}$ were different between P5 and P8. P5 had only five cooling cycles and P8 had nine, in order to keep $\overline{T}_{sk}$ below 34.5°C and above 33.5°C. Given that P5 felt slightly cool by 20 min of exercise, and remained slightly cool throughout exercise according to the TS data, the case can be made that P5 might have preferred to have the lower $\overline{T}_{sk}$ limit of 33.5°C raised to a warmer temperature. He might have even preferred to have the upper limit raised to a temperature warmer than 34.5°C. Alternately, he might have been more comfortable if the temperature of the liquid coolant had been raised to a higher temperature. However, P5's data in Figure 2 show that $\overline{T}_{sk}$ was about 1°C warmer in PC$_{skin}$ than in PC.

Now, if one looks at the $\overline{T}_{sk}$ in Figure 1 for the PC$_{skin}$ cooling paradigm, the TS data warrant exploring the possibility of increasing the liquid coolant temperature circulating in the cooling garment. It is possible that the pump could be deactivated at a temperature >33.5°C. Although there was little difference in electrical power used (P5: 108 W; P8: 116 W), P8 had 23 W more heat extracted, or cooling, than did P5.

The effect of raising the liquid coolant temperature in the PC$_{skin}$ cooling paradigm is being explored by biophysical modeling based on the current study. If the modeling effort supports the idea that the liquid cooling temperature can be raised in the PC$_{skin}$ cooling paradigm, as deduced from the TS data in the current study, further power savings may be possible. CC and PC cooling paradigms also need to be further explored to determine the optimal coolant temperature and to apply our findings for individual considerations and preferences, as Nevins, Gonzalez, Nishi, and Gagge (1975) recommended earlier.

The choice to measure TS and TC perceptions during the study could be debated, because the nature of the experiment included changing $\overline{T}_{sk}$ by design when T_c was also changed as the men walked. However, $\overline{T}_{sk}$ has been shown in subjective TC and TS ratings to be weighted more heavily (Frank, Raja, Bulcao, & Goldstein, 1999), which supports the focus of this study and the important findings from PC$_{skin}$. There was a significant difference in T_c ($p = .035$) between the morning and late morning trials, which was expected, given the circadian variation in T_c. The participants were controlled as whether they participated in the morning or the late morning session (Stephenson et al., 1984). The participants were kept fairly comfortable and, according to the ESQ, were not stressed.

In hindsight, to make the PC$_{skin}$ test more sensitive, more measurements of thermal perceptions could be taken during exercise. To avoid a potential limitation of the study, more participants might have been tested, although the power analysis done prior to the study showed we had an adequate number. TS and TC measurements in PC$_{skin}$ varied because the cooling was determined by skin temperature, so there were some instances when the cooling was on or off during data collection and thus was not consistent between the participants. Despite these drawbacks, the TC, TS, and ESQ measures provided the necessary information to answer the question of whether the men were as comfortable during exercise when cooling was activated less under the integrative approach of PC$_{skin}$, as compared with CC and PC.

CONCLUSIONS AND RECOMMENDATIONS

The current subjective findings on thermal perception, combined with those of Kolka et al. (2004) and Stephenson et al. (2007), provide strong evidence to support the development of a cooling garment that can be controlled by the individual's $\overline{T}_{sk}$ to manage heat stress for longer periods of time for a given battery power. Commercial development of the prototype PC$_{skin}$ will provide better cooling and, thus, improved operational capability. Future analyses of the optimal liquid coolant temperature could lead to further improvement in power savings as compared with CC and PC and to improved individual perception of thermal comfort and sensation. Additional research should determine how a number of factors (e.g., exercise intensity, exercise duration, and hotter ambient temperature) might change subjective perception of the PC$_{skin}$ cooling paradigm.

ACKNOWLEDGMENTS

We gratefully acknowledge the volunteers who

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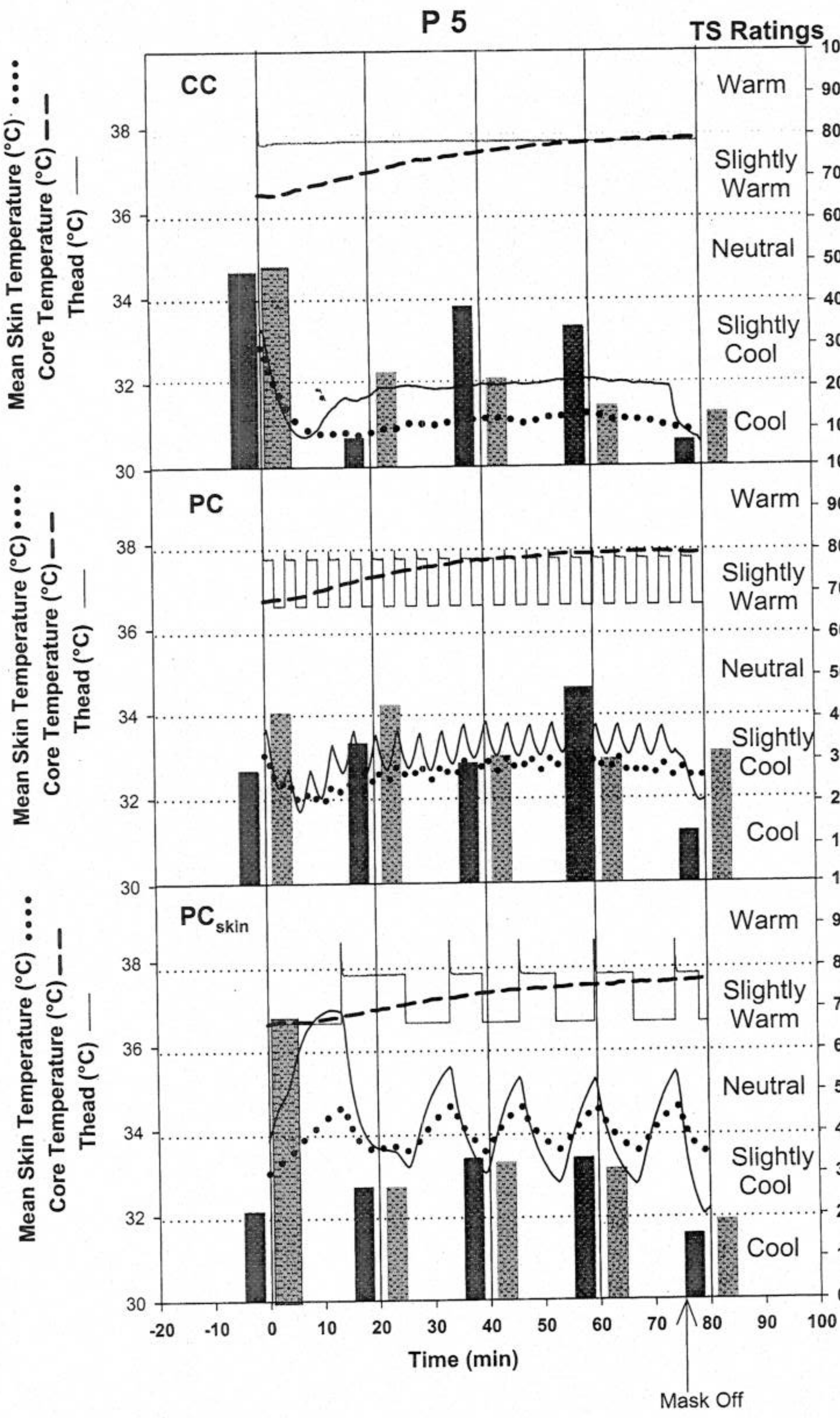
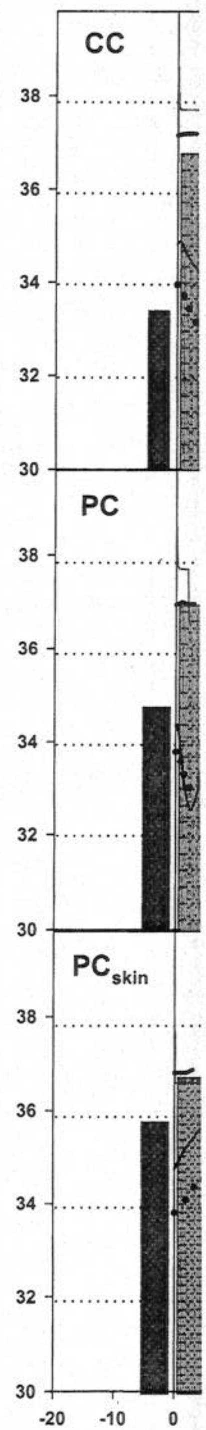


Figure 2. Mean skin temperature ($\overline{T}_{sk}$), core temperature (T_c), head temperature (T_{head}), perfusate status, thermal comfort, and thermal sensation (TS) for the three cooling methods (CC = constant cooling, PC = pulsed cooling, PC_{skin} = PC regulated by mean skin temperature; see text for details) for 2 participants (P5 and P8). The top line for each



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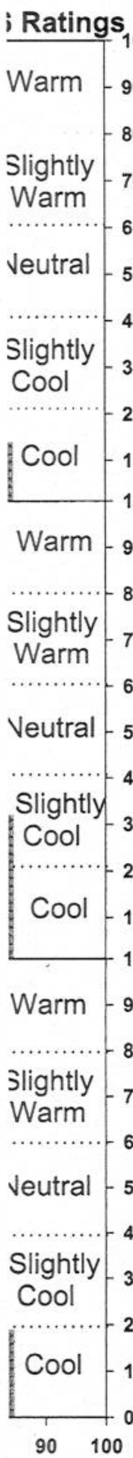

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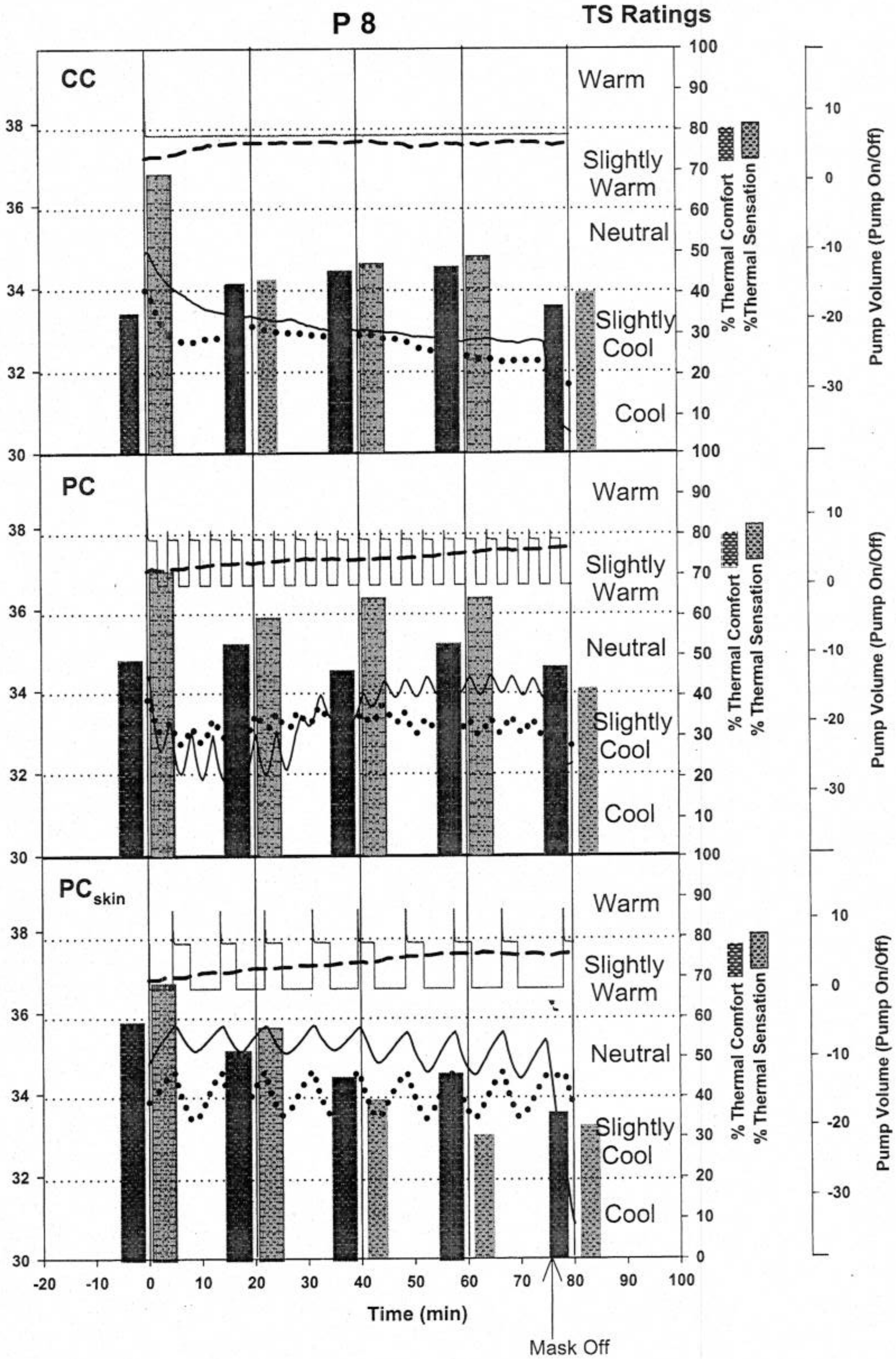

panel shows T_c, the middle line shows T_{head}, and the bottom line shows $\overline{\overline{T}}_{sk}$. The faint lines in the bottom 2 panels for both P5 and P8 (in the Slightly Warm to Warm sections) demonstrate the cooling pump activation and inactivation (right axis).

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Human participants took part in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USARMC Regulation 70-25 on the Use of Volunteers in Research. For protection of human participants, the investigators adhered to policies of applicable Federal Law CFR 46.

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